Recommendations for a Department of Energy Nuclear Energy R&D Agenda

Appendix 2
Nuclear Energy Related R&D in the United States

EXECUTIVE SUMMARY

Most of the nuclear energy-related research and development (R&D) in the U.S. is done by six organizations: the U.S. Department of Energy (DOE), the Electric Power Research Institute (EPRI), the U.S. Nuclear Regulatory Commission (NRC), the Westinghouse Owner's Group, the Boiling Water Reactor Owner's Group, and the Babcock & Wilcox Owner's Group (there is no Combustion Engineering Owner's Group). Some limited R&D is done by individual utilities and by the reactor fuel vendors. The DOE, EPRI, and NRC budgets have been in the range of $60–90 million per year in recent years. The Owners' Group budgets are somewhat lower.

The goals and objectives, organization of the work, focus of the R&D, type of contract support, and final products of the DOE, EPRI, and NRC R&D are not the same. The DOE tends to sponsor a few large programs that, if successful, will make a significant impact on the use of nuclear power in the U.S., respond to certain international obligations, or support other Federal responsibilities such as spent fuel disposition. EPRI tends to sponsor a much larger number of smaller, shorter-term R&D projects that are focused on safe, environmentally benign, and cost-effective *plant performance*. The EPRI projects are organized around utility operational areas (for example, technologies to improve fuel reliability, reduce low-level waste, reduce operation and maintenance costs, etc.) and are expected to produce products that will be used by the utilities. The NRC also has many small R&D projects. But the NRC Office of Research projects are organized around certain technical disciplines (for example, thermal-hydraulics, materials aging, reactor structural performance, probabilistic risk assessment, etc.), and much of the exploratory research is concerned with advancing the state-of-the-art of the technology and thereby staying ahead of industry and putting the NRC in a position to make authoritative judgments. The R&D sponsored by the NRC Office of Research also responds to research requests from the Office of Regulation and to questions from the public, the Commissioners, and others. The Owner's Group programs are somewhat similar to the programs sponsored by EPRI and primarily focus on current material aging issues and operation and maintenance cost savings items. However, the Owners Group programs are somewhat more involved with component aging mitigation and replacement technologies (for example, new bolting or pump shaft materials and designs), improved instrumentation and control, and operational procedures.

1.0 U.S. DEPARTMENT OF ENERGY SPONSORED R&D

The Clinton administration's nuclear energy policies include:

- Maintaining the safe operation of the existing nuclear power plants (NPPs) in the U.S..
- Retaining the option to construct a next generation of NPPs.
- Promoting nuclear safety worldwide.
- Expediting the characterization of the geological repository for high-level waste.
- Concluding an agreement with Russia to dispose of excess nuclear weapons materials by burning the plutonium in commercial reactors.

The most recent Congressional direction is contained in the Energy Policy Act of 1992 and requires the DOE to carry out its civilian nuclear programs in a way that will lead toward commercial availability of advanced nuclear reactor technologies, including technologies that use standardized designs or exhibit passive safety features. In response to these policies and directions, DOE has been sponsoring (or plans to sponsor) the development of three advanced light water reactor designs, technologies to support the implementation of reactor-based plutonium disposition in the U.S. and Russia, technologies to help assure the economic and safe operation of the existing NPPs through current and renewed license terms, and technologies to minimize the generation of spent (used) nuclear fuel.

1.1 Advanced Light Water Reactor Program

The objective of this program was to make available standardized nuclear power plant (NPP) designs with certification by the NRC and do so in a joint cooperative effort with industry. The designs will provide enhanced safety and reliability and will meet the needs of the electric power utilities as reflected in the Utilities Requirements Document developed in conjunction with the utility industry through the EPRI. When employed with advanced plant modularization and prefabrication techniques, pre-certified, commercially standardized ALWR designs will offer the prospect of significantly improved competitiveness through reductions in life-cycle costs and construction time. The program is a cooperative cost-shared effort with the nuclear industry (foreign and domestic).

Three new standardized ALWR plant designs are currently under development. The two evolutionary plant designs were certified by the NRC in 1996. They are called “evolutionary” designs because they build directly on the experience and lessons learned from the NPPs already operating in the U.S. and around the world. However, the ALWRs will be easier to build, operate, and maintain and they will meet safety goals that are more than ten times more stringent than those of current plants. The two evolutionary designs are the General Electric (GE) Advanced Boiling Water Reactor (ABWR) and the ABB Combustion Engineering (ABB-CE) System 80+, both of which are large (1,350 MWe) plants.

The third standard design, referred to as the AP600, is being developed by Westinghouse Electric Corporation and is a smaller 600-MWe pressurized water reactor (PWR) design that uses “passive” safety features. The passive design employs conventional reactor and power generation technology but uses passive features for safety functions that are performed in current and evolutionary plant designs with active systems that use pumps and motors. This design is expected to be certified by the NRC in 1999. Once a design is certified, a utility may acquire the plant without further NRC review of the design, except for any changes from the certified design.

A fourth standard design, General Electric’s Simplified Boiling Water Reactor (SBWR), was also under development as part of the ALWR program. General Electric terminated the SBWR project in March 1996 to pursue a larger, passive BWR design.

The second part of the ALWR Program is the First-Of-a-Kind Engineering (FOAKE) Program. The specific objectives of this program are to perform detailed engineering beyond what is required to make a safety determination of two competitively selected ALWR designs in order to promote design standardization and facilitate firm and reliable cost estimates and construction schedules.

Advanced Boiling Water Reactor

The design for the ABWR differs from today’s BWR in a number of ways:

(1) Safety improvements resulted in a more compact design; the ABWR’s building volume is only about 70% of that of current operating BWRs. This will reduce construction time and cost. It also makes the design more rugged and more immune to earthquake.

(2) In the ABWR, the control rods are driven by electro-hydraulic systems as opposed to the simpler hydraulic design in the current BWRs. Having an additional drive mechanism reduces the probability of failure and improves the plant's ability to produce electricity and to meet changes in electricity demand.
(3) All major equipment and components have been engineered with service and maintenance in mind so as to minimize downtime and reduce worker exposure to radiation.

Two ABWRs, which are very similar to the design certified in the United States, have been under built Japan. The first unit began operation in January 1996, and the second unit began commercial operation in July 1997. The total construction schedule for these plants was about five years.

System 80+

Like the ABWR, the System 80+ PWR is a simpler design and is engineered to achieve improvements in cost and safety with a number of significant features:

(1) The volume of cooling water is greater than in the current ABB-CE plants, the System 80+ plant operates at lower temperatures, and the power density in the fuel is lower.
(2) Design margins are increased, reliability of existing systems is increased, and new safety systems are added.
(3) The control room and information processing systems have been totally revamped in ways that will reduce the burden on the operators and improve comprehension.
(4) The steam generator design incorporates advances in materials technology and has also been improved for ease of maintenance.
(5) The reactor is housed in a very large steel dual containment designed to withstand any credible accident.

Two ABB-CE System 80 units under construction in South Korea incorporate many of the advanced design features of the System 80+. Through ABB-CE's simplified design, the construction time can be reduced to only 48 months from first pouring of concrete to fuel load.

AP600 Passive Plant

The AP600 plant design is considered "passive" because the safety systems predominantly depend on the reliable natural forces of gravity, convection, evaporation, and condensation instead of operator actions, AC power supplies, and motor driven components. The AP600 has several large tanks of emergency cooling water inside the containment structure above the reactor vessel. During an emergency, pressure and gravity assure that the reactor core is fully cooled. The main passive safety systems include:

(1) Decay heat removal by a natural circulation heat exchanger using water stored inside the containment.
(2) Passive safety injection systems:
    - Gravity flow core makeup tanks at high pressure.
    - Nitrogen pressurized accumulators.
    - A gravity drain refueling water storage tank at low pressure.
    - Gravity drain from the containment.
(3) Passive containment cooling by natural circulation of air and gravity flow of water.
(4) Emergency heating, ventilation, and air conditioning in the control room—compressed air and concrete walls as the heat sink.
(5) Low power density core.

Because of their simplicity, these smaller plants can be built much faster than recently completed U.S. nuclear plants. Quick construction (3 to 4 years) is possible because many systems and subsystems would be assembled as modules in the factory, not on the plant site. Some of the important design features are:

(1) A reactor coolant pump design with canned rotor pumps.
(2) Fifty percent fewer valves, 35% fewer pumps, 80% less pipe, 45% less seismic building volume, and 70% less cable than a comparable conventional 2-loop 600-MWe plant.
(3) A plant arrangement to enhance construction, operation, maintenance, and safety, and to lower costs.
(4) Construction with modular systems and structures.

The AP600 design certification program included the initial plant design activities as well as the current activities related to the NRC design certification review process. A major test and analysis program was included to demonstrate the performance of the new passive design features and to provide a basis for the safety analysis of the AP600. Westinghouse used several test facilities in the United States and abroad to conduct extensive tests to prove the operation of the plant's passive safety features. A detailed analysis of the test results showed that the computer codes used for this design are valid and accurately predict plant behavior under normal and accident conditions.

FOAKE Program

In February 1992, DOE and a consortium of electric utilities called the Advanced Reactor Corporation (ARC) entered into a Cooperative Agreement for a five-year, cost-shared program to do detailed “First-Of-A-Kind Engineering” on at least two standardized ALWRs. The FOAKE Program implements requirements of the Energy Policy Act of 1992. This program completes much of the detailed, standardized engineering work that goes beyond what the NRC requires to conduct safety reviews and will provide the level of information needed by potential buyers to estimate construction costs and schedules with a high degree of certainty.

Two designs—GE’s 1,350 MWe ABWR and Westinghouse’s 600 MWe AP600—were selected in January 1993 by ARC to share FOAKE support. ARC manages the FOAKE Program under the overall guidance provided by DOE, assuring in-depth utility technical input and coordination in the management and performance of the program. The FOAKE Program for the ABWR design was completed in 1996. Completion for the AP600 is projected in 1998.

The goal of the FOAKE Program is to develop the engineering design for the site-independent features for the plant to a level of detail sufficient to define credible cost estimates and construction schedules to provide a baseline for achieving commercial standardization. A primary objective of FOAKE is to complete engineering to the point where essentially the only design work remaining is:

(1) Procurement of equipment and material, and completion of necessary detailed design work that flows from that action.
(2) Adaptation of the design to the specific site on which the plant will be built.
(3) Incorporation of as-built information necessary as a result of the normal construction process, subject to strict control procedures that would discourage changes for other than unavoidable reasons.

The FOAKE Program will complete the ABWR and AP600 designs to the point of preparing specific procurement specifications for a predetermined set of major components that have long lead times for fabrication. For the remainder of the plant components, standardized performance requirements and specifications are to be defined on a basis of “form, fit, and function” in order to avoid unduly limiting competitive offers from component vendors at the time of plant acquisition.

1.2 Mixed Oxide Fuel R&D

The goal of the program sponsored by DOE's Office of Fissile Materials Disposition (DOE/MD), is to conduct the R&D necessary to support the implementation of reactor-based plutonium disposition in the U.S. and Russia. Current efforts focus on four generic areas: (1) development and demonstration of mixed oxide (MOX) fuel and cladding technologies; (2) fuel fabrication facility, reactor, and fuel cycle computational methods assessment, development, and applications; (3) fuel packaging and transportation technologies; and (4) economic evaluations of fuel fabrication facility and reactor operations.

Fuel and Cladding Technology Development

The first major activity focuses on the development of an improved understanding of fuel-side clad corrosion mechanisms and fuel reliability and performance issues. The ultimate goal of this effort is to provide guidance necessary for specifying impurity limits in MOX fuels, and to support licensing of these fuels for use in commercial light water reactors. DOE/MD is sponsoring both out-of-pile, and in-pile experimental programs to provide a better understanding of the behavior of chemical impurities in the fuel matrix, the transport of these impurities to the fuel/clad interface, and the potential interactions of these impurities with the fuel cladding material. The major impurity of interest is gallium.

DOE/MD is also sponsoring a joint U.S./Russian project to develop, test, and qualify weapons-grade VVER-1000 MOX fuels for use in Russia. The MOX fuel for these tests will be fabricated at the Bochvar Institute in Moscow and irradiated in the MIR test reactor at the Research Institute of Atomic Reactors (RIAR) in Dimitrovgrad. The U.S. is working with these Russian institutes to design the test, develop the fuel specification, fabricate the test fuel, perform the irradiations, and conduct the required post-irradiation examination.

Computational Methods

A significant computation effort is underway to identify and evaluate fuel and fuel-cycle management strategies to accommodate various disposition mission contingencies. This work includes detailed neutronic evaluations of various mixed low-enriched uranium and MOX core geometries, and the identification of reasonable fuel and core design options to achieve variable plutonium disposition rates through the reactor.

DOE/MD is also sponsoring a detailed evaluation of previous U.S. commercial MOX fuel tests to identify data of potential utility for benchmarking of U.S. physics, neutronics, and safety codes and to apply the data in benchmarking and validation exercises. Additional new data is being obtained via participation in the international ARIANE Program, in which Belgium, France, Japan, England, and other nations are obtaining detailed data on both PWR and BWR commercial low-enriched uranium and MOX fuel performance at a variety of burnups and thermal conditions.

The Oak Ridge National Laboratory (ORNL) is the U.S. co-chair of the Joint U.S./Russian Working Group on thermal reactor- and fast reactor-based plutonium disposition and has the lead for coordinating the joint U.S./Russian efforts related to benchmarking of the U.S. and Russian computer codes. Researchers at ORNL, Texas A&M University, Kurchatov Institute (near Moscow), and the Institute for Physics and Power Engineering (near Obninsk) are working together to benchmark and validate a suite of U.S. and Russian computer codes required for criticality, physics, safety, and thermal hydraulic analyses of fuel fabrication facilities, reactors, and fresh and spent fuel shipping containers.

Fuel Packaging and Transportation Technology

Approximately 1500 to 3000 MOX fuel assemblies will be required for disposition of the U.S. surplus plutonium inventory. Current fuel shipping containers only accommodate two PWR assemblies. DOE/MD is currently sponsoring the design of an improved, high-capacity, fuel shipping container that would provide major advantages over existing shipping container options. These advantages include higher fuel capacity (two to three times as much fuel per container), and easier handling of the fuel container at the reactor site.

Fuel Fabrication Facility and Reactor Economics

DOE/MD has recently completed an evaluation of the cost and economic implications of construction and operation of a domestic MOX fuel fabrication facility, and conversion and operation of existing light water reactors for the plutonium disposition mission.

1.3 Nuclear Energy Security

The DOE Nuclear Energy Security Initiative focuses on research and development of technologies needed to help assure the economic operation of the existing U.S. NPPs through their current and renewed license terms, while at the same time enhancing safety and minimizing the generation of spent nuclear fuel. This will help maintain the current share of nuclear power generation in the U.S. and preserve the option to increase its use in the future.

One hundred and nine NPPs now provide about 22% of the electricity generated in the U.S. These plants have proven to be a reliable source of baseload power. However, five NPPs have closed prematurely since 1989 due to age-related problems such as steam generator tube degradation and reactor pressure vessel embrittlement. In addition, the licenses for 48 of the currently operating plants will expire by 2015. Key technological issues and significant regulatory uncertainty threaten the license renewal option for many of these plants, which would otherwise be cost-competitive. Also, the lack of a deep geologic repository, located at an isolated and arid location, has resulted in used fuel piling up at NPPs in 41 states and, at some plants, political pressure for premature shutdown. The potential loss of nuclear baseload electricity generation capacity, compounded by the expected future growth in electricity demand, will have a significant impact on U.S. carbon emissions. This initiative proposes to conduct critical research and development of technology that is needed to address issues of age-related degradation and equipment obsolescence, and to develop ultrahigh-burnup fuel (and thereby minimize the amount of used fuel being discharged from the U.S. NPPs). This initiative also includes funding to support DOE's participation in selected international programs and to maintain certain critical university research capabilities. By achieving its objectives, the Nuclear Energy Security initiative will help the U.S. maintain its strong leadership position in the world to positively influence nonproliferation, global climate change, and reactor safety worldwide.

Maximizing Benefits from the U.S. Investment in Nuclear Power Plants

Technologies will be developed that can help maintain the continued safe, reliable, and economic operation of existing U.S. NPPs throughout their current and renewed license terms. To achieve this goal, the Department will accomplish the following objectives:

(1) Develop technologies to inspect, characterize, and manage the effects of aging on key nuclear plant systems, structures, and components that impact safety and operation.
(2) Develop technologies to improve plant operation and control, relieve critical equipment obsolescence issues, and enhance plant performance and economics while maintaining safety.
(3) Develop technologies to reduce the costs and regulatory uncertainties for license renewal.

The materials used in some NPP components can be damaged by the temperatures, stresses, and radiation that are associated with the normal operation of the plants. To assure the economic and safe operation of these plants, it is necessary to predict and measure the extent of this material damage and to determine its effect on the ability of the components to perform their design functions. It is also sometimes necessary to take appropriate and cost-effective actions to mitigate the effects of this degradation. Examples of key component-aging degradation include reactor pressure vessels embrittled after decades of operation in intense radiation fields; reactor internals damaged by stress corrosion cracking; instrumentation and electrical cables damaged after long-term exposure to radiation and high temperatures; and steam generator tubes cracked or degraded in harsh chemical or stress environments.

The instrumentation and control (I&C) systems in today's nuclear plants are based on technology developed in the 1960s and have been overtaken by the revolution in digital and computer technology. Spare parts for these old control systems have become increasingly scarce, in some cases nonexistent, increasing the potential for equipment failure or human error. Modern digital and microprocessor-based I&C technologies, while used extensively in the process and petrochemical industries, have not been designed and approved by the NRC for application in NPPs. In much the same way that modern digital controls and ergonomics make today's advanced jet liners safer and easier to fly than the aircraft of 25 years ago, modern advances in I&C technologies, man-machine interface techniques, and advanced information management systems could provide many benefits in the operation of NPPs. The DOE proposes to help the nuclear industry implement those advances.

The DOE technologies to inspect, characterize, and manage the effects of aging on key NPP systems, structures, and components and the DOE technologies to improve plant operation and control, relieve equipment obsolescence issues, and enhance plant economics while maintaining safety will then provide a basis for the nuclear industry to address the uncertainties associated with license renewal.

Spent Fuel Minimization Research and Development

The objective of the program is to minimize the amount of spent fuel discharged from the 109 commercial NPPs now operating in the United States. The specific goals are to (1) reduce the rate of spent fuel generation by 25% in seven years and cut the rate in half in 15 years and (2) improve the reliability and safety margins of LWR fuel. A reduction in the rate of spent fuel generation by one half and use of high burnup cores in the U.S. NPPs will reduce the cost of the DOE Civilian Radioactive Waste Management Program by $1–8 billion, help improve NPP capacity factors by 5–9% (which is equivalent to adding 5–9 1000 MWe NPPs to the existing fleet), reduce pressures on temporary fuel storage facilities, and significantly reduce worker exposure and the amount of low-level waste produced by the nuclear power industry.

The LWR fuel is currently limited to (a) 60 GWD/MTU peak rod burnup by the NRC because of concerns about high-burnup fuel integrity, and (b) less than 5% enrichment because of the design and licensing of the fuel fabrication plants and handling and storage equipment. In addition, the control rod worths and other aspects of the core neutronics designs may have to be modified to allow the use of significantly higher burnup fuel. Therefore, the program will address the following issues: high-burnup fuel integrity; high-burnup core design; equipment and procedural changes required to fabricate, ship, store, and handle higher enriched and higher burnup fuel; and the changes in equipment reliability and the surveillance and maintenance intervals required for extended refueling cycles. The most difficult challenge will be to develop a fuel with improved reliability and safety margins that can be operated to very high burnups. Most of the U.S. utilities are somewhat reluctant to extend the burnup of their fuel because the costs of handling failed fuel can be quite high, possibly requiring an unscheduled shutdown of the reactor.

The planned program will include a three-part approach:

(1) Determine the useful life of the best fuel currently in commercial NPPs.
(2) Develop a better fundamental understanding of the life-limiting degradation mechanisms at high-burnup.
(3) Design and test advanced and innovative LWR fuel forms.

The research with the commercial spent fuel will include characterization of the condition of modern fuel that has been burned in commercial NPPs to the current limits, further irradiation of this fuel in a test reactor to ultra-high burnups, and design basis accident testing to assure that the fuel will meet the current NRC licensing criteria. Both loss-of-coolant (LOCA) and reactivity initiated accident (RIA) tests will be conducted. A complete set of results, including appropriate computer models, should be available in about six to seven years.

The development of the advanced fuel will be done in collaboration with the international fuel vendors and fuel experts at the various national laboratories. The various advanced fuel designs will probably first be irradiated in a test reactor (including power ramp tests) and then removed, examined, and subjected to transient testing. Some advanced fuel may also be placed in lead test assemblies (LTAs) in commercial NPPs and then moved into a test reactor for further irradiation and transient testing.

In parallel with the irradiation of the advanced design fuels in the test reactors, laboratory research to study the metallurgical and environmental factors that affect the degradation (corrosion and radiation hardening) of the fuel cladding and analysis to evaluate fuel designs that better retain the fission products within the fuel, have more uniform rod internal pressure, and minimize fuel-cladding mechanical interactions will be conducted. This work will be a collaborative effort involving national laboratories as well as fuel vendors and a number of universities.

The products available for use in the commercial nuclear power industry include:

(1) A thorough evaluation of the useful life of the best fuel currently being sold by the fuel vendors at the end of 7 years. We expect that a number (maybe all) of the latest product lines can be used at burnups above the current U.S. NRC limit of 60 GWD/MTU.
(2) Development of initial testing of advanced ultra-high-burnup fuel designs, sufficient for the vendors to start selling lead fuel assemblies at the end of 7 or 8 years.
(3) A well-documented physical understanding of the metallurgical and environmental factors that affect cladding (and assembly structural material) degradation. Improved fuel and fuel assembly predictive models and a solid technical basis for the sale and licensing of advanced fuels will be developed at the end of 15 years.

International Collaboration

Participation in international programs:

(1) Helps maintain U.S. leadership and influence in the international application of nuclear technologies.
(2) Helps open new markets to U.S. industry to create new, high-technology jobs in the U.S..
(3) Helps provide U.S. access to overseas expertise, technology, and research capabilities to reduce program costs.

Much of this work will be done through two important international organizations: the Nuclear Energy Agency of the Organization for Economic Cooperation and Development (OECD/NEA) and the United Nation’s International Atomic Energy Agency (IAEA). Collaboration through OECD/NEA will allow DOE to use certain international facilities and program activities to leverage domestic investments in related activities. Research areas of interest include high-burnup-fuel performance and safety, aging degradation of selected NPP materials, and man-machine systems research. The DOE also plans to continue its leadership and participation in the IAEA in areas related to enhancing the safety, performance, and reliability of commercial NPPs.

The DOE also has several important international bilateral agreements, including work with Russia to help them improve the safety of their nuclear facilities and an agreement with Japan to develop advanced robotic systems for decontamination and decommissioning projects. The DOE has also been working with a number of countries to help resolve certain severe accident issues so as to complete the development of a suite of advanced severe accident management tools for use in the U.S. and elsewhere.

The U.S. has a very important strategic interest in assuring that the overseas nuclear energy growth takes place with an emphasis on safety and on minimizing proliferation risks. The U.S. has been the world leader in nuclear safety and nonproliferation issues in the past; however, if the U.S. is to continue to have a significant voice in the international arena, the U.S. must maintain an active nuclear industry and remain engaged on a government level. In addition, the worldwide growth of nuclear power provides a broad market for U.S. industry. The U.S. has the safest, most advanced NPP designs in the world, and the sale of these designs could provide significant economic benefit to the country.

Maintaining Critical University Research Capabilities

An effort is proposed under the Nuclear Energy Security program to involve the nuclear engineering departments at the U.S. universities in the individual research areas discussed above. Specifically, the Department proposes to set aside a fixed portion (about 10–15%) of the program funding to sponsor university research that supports the goals and objectives of the Nuclear Energy Security Program. This will:

(1) Help maintain a valuable part of the nation’s science and technology base.
(2) Apply the creativity and energy available in U.S. universities to solve real-world technology problems at low cost.
(3) Encourage talented students to study the radiological sciences, which are needed for broad application in today’s high-technology economy.

The Department regards universities as integral team players on the program and seeks the involvement of young scientists and engineers who can work with experienced researchers and professionals on these programs. University participation and input will be encouraged in team program reviews, work plan meetings, and technology reviews. Student participation in the conduct of university R&D support work will be required as a condition for eligibility to receive funding.

2.0 ELECTRIC POWER RESEARCH INSTITUTE SPONSORED R&D

EPRI's nuclear energy related research and development is conducted by the Nuclear Power Group. The goal of the Nuclear Power Group is to provide the integrated technology base essential to achieve safe, environmentally benign, and cost-effective plant performance. This should promote the regulatory stabilization and cost competitiveness required for a renewed expansion of nuclear power. The EPRI R&D program is organized around the six *targets* discussed in the remainder of this section and is supportive of the short-range economic interests of EPRI's nuclear members and their stakeholders.

During the past two decades, more than 400 R&D products have been developed and delivered by the Nuclear Power Group. Noteworthy developments include operational guidelines to prevent and control steam generator tubing degradation in PWRs; remedial measures for BWR pipe stress corrosion cracking; radiation reduction technologies; state-of-the-art safety analysis methods; cost-saving maintenance, engineering, and human factors guides; advanced nondestructive examination (NDE) technologies; and requirements for advanced light water reactors ALWRs. The CY-1997 budget for those activities was approximately $84 million.

2.1 Advanced Nuclear Technology Target

The objectives of this target are to: (1) develop investment-ready nuclear energy options that have the potential for economic implementation around the turn of the century; (2) follow developments related to advanced reactor concepts and perform joint studies with utilities, government, and international organizations; (3) explore innovative ideas that have a high potential for reducing the cost of operating current plants; (4) conduct limited, but effective, exploratory research, in a highly leveraged way, to support the resolution of corrosion issues in NPPs, and, in particular, extend the life of components that are subject to high radiation doses and may be limiting to economical plant life extension; and (5) develop integrated solutions that can simplify the management and reduce the cost of designing, building, operating, maintaining, and decommissioning nuclear plants.

Activities completed include Utility Requirements Documents for Evolutionary ALWRs and for Passive ALWRs, and the NRC Safety Evaluation Reports on these documents. Ongoing projects include (1) designs for investment-ready Westinghouse AP600s; and (2) validated stress corrosion cracking models. Future projects will include (1) the development of tools to simplify management and reduce the cost of designing, building, operating, maintaining, and decommissioning NPPs; and (2) selected studies on the technical and economic issues surrounding the advanced reactor concepts.

2.2 Fuel Reliability, Storage, and Disposal Target

This target focuses on increasing fuel reliability by identifying the root causes of fuel failures and providing technologies for evaluating vendor-proposed new designs or remedies. Significant resources are directed toward lowering overall fuel-related operations and maintenance (O&M) costs, providing cost-effective and licensable methods for on-site storage of spent fuel, developing and delivering technical bases that support long-term storage, facilitating the transfer of spent nuclear fuel to the DOE, and helping DOE develop a cost-effective and timely high-level waste repository.

Activities completed include guidelines on fuel reliability and ESCORE (a computer program for fuel burnup extension), Boraflex guidelines, and on-site storage technologies such as NUHOMS and metal casks. Future and ongoing products include technical evaluations of postfailure fuel degradation, reactivity insertion accident criteria, fuel performance, burnup extension, and impact of water chemistry on fuel cladding corrosion. Other products include R&D that will enable efficient use of multipurpose canisters by utilities, produce a detailed design of a spent fuel transfer facility, remedial measures to address Boraflex degradation, transportation technology, and improvements in the EPRI-developed performance assessment code (IMARC) that will assist in repository licensing.

2.3 Low-Level Waste, Chemistry, and Radiation Control Target

This target provides technology to reduce low-level waste (LLW) sources, minimize LLW volumes, develop storage options, control water chemistry to minimize corrosion and the input of corrosion products, improve radiation protection procedures, and control out-of-core radiation fields. Recent developments include the LLW characterization guidelines, amines for PWR secondary system pH control, the NOREM cobalt-free hardfacing alloy, the BWR zinc injection passivation process, and improved LOMI and EPRI DFD decontamination processes. Other activities completed include guidelines on LLW interim on-site storage and mixed waste management and updated PWR/BWR water chemistry guidelines. Software products include the LLWWASTECOST modules, chemWORKS simulator for PWR/BWR plants, and DERAD decommissioning economics and risk advisor.

Revisions to the above products will incorporate new plant experience and technical developments. Future products include the EPRI wasteWORKS software for evaluating dry and liquid waste processing options; the EPRI SMART chemWORKS software for real-time water chemistry control; a technical evaluation of advanced technologies for LLW and mixed waste management including liquid waste management guidelines and demonstrations of the BWR depleted zinc-64 injection, various improved decontamination processes, and a chromium passivation process for replacement components; guidelines on effective dose equivalent implementation and application of water chemistry developments, including improved PWR amines and BWR feedwater iron reduction; and software/guides on evaluating decommissioning technology developments.

2.4 Major Component Reliability Target

The objectives of this target are to reduce and control the cost impact of corrosion-related damage in steam generators, pressure vessel penetrations, piping, reactor vessel internal components, and steel containments; and to develop cost-effective means to manage radiation embrittlement and maintain serviceable reactor pressure vessels. Activities under this target have resulted in technology, information and tools for managing degradation of major components. Previous results have been applied to manage the residual life of steam generators and to improve their reliability and have resulted in avoided costs of >$5 billion in PWR plants since 1978. Ongoing work on degradation-specific management is expected to delay steam generator replacement or derating by up to five years and to further improve reliability. A series of products related to mitigation and repair of stress corrosion cracking have resulted in avoided costs of >$2 billion in BWR plants since 1981.

Current projects are producing water chemistry remedies applicable to degradation of steam generator tubing, vessel head penetrations, and BWR vessel internals. Products related to BWR vessel internals will include evaluation, inspection, repair, and mitigation guidance. This guidance will be disseminated as BWR Vessel & Internals Projects (BWRVIP) products. Corrosion-related technology applications will be delivered through the CHECWORKS software workstation. Planned repair-related developments are also applicable to pressure vessels, internals, and steam-generator tubing. Another group of planned products includes evaluation methods, data, and computer codes for managing reactor vessel radiation embrittlement. Thermal annealing for restoration of properties is a related product objective.

2.5 O&M Cost Control Technology Target

This target involves development and delivery of technology that contributes to successful utility cost-control programs. Activities completed include a comprehensive set of tools to implement least-cost, reliability-centered maintenance; validated models to predict the performance of motor-operated valves; a handbook to assist plants in avoiding fatigue-related failures; the development of technology centers and programs such as the Nuclear Maintenance Applications Center, the Nondestructive Evaluation Center, and the Plant Support Engineering program; I&C guidelines on licensing digital upgrades and electromagnetic interference and software verification and validation; and the technical basis for an improved license renewal rule and life-cycle management (LCM) evaluations of key systems and structures.

Future and ongoing activities include integration of preventive maintenance technologies with predictive maintenance techniques; evaluation of in-situ piping rehabilitation; demonstration of LAMB wave ultrasonic inspection of heat exchanger tubing; application of risk-based inspection; the timely development of maintenance and engineering guides, periodicals, and databases; further development of the test bank for use in assessing maintenance personnel proficiency; I&C LCM guidance and results from host plant demonstrations of I&C modernization; and application of LCM products to specific nuclear unit issues.

2.6 Safety and Reliability Assessment Target

The objectives of this target are (1) to deliver risk and reliability technology aimed at reducing O&M costs without compromising safety, (2) to develop and deliver analysis methodologies needed to resolve regulatory issues and to perform independent reload and plant operational safety analyses, and (3) to ensure a stable regulatory environment linked to quantitative safety criteria that permits industry resource allocations proportional to risk. Results and products completed in the target include outage risk assessment and management software; Seismic Qualification Users Group methodologies; a motor-operated valve ranking methodology; Individual Plant Examination (IPE) and Individual Plant Examination of External Events (IPEEE) software products; and the widely used safety codes RETRAN, VIPRE, GOTHIC, and MAAP. Application of EPRI’s risk assessment technology has supported reduced containment leak testing under the revised 10 CFR Appendix J. EPRI’s PSA Applications Guide is being utilized by industry analysts in conjunction with risk-based in-service testing and other applications.

Ongoing and future efforts include more outage management technology, seismic equipment qualification databases and guidelines, Appendix B (Q/A) cost reduction, on-line maintenance support software, performance-based fire protection, the risk and reliability workstation to integrate and improve the efficiency of using PSA software, integration and in-plant application of the safety codes, application of the revised source term to reduce equipment qualification costs, and timely solutions to severe accident management implementation issues.

3.0 U.S. NUCLEAR REGULATORY COMMISSION SPONSORED R&D

3.1 Office of Nuclear Regulatory Research

The Energy Reorganization Act of 1974 mandated the formation of the Office of Nuclear Regulatory Research to ensure that the Commission would have "an independent capability for developing and analyzing technical information related to reactor safety, safeguards, and environmental protection in support of the licensing and regulatory process." The current NRC research program includes both confirmatory and anticipatory research and focuses on areas with high safety and regulatory significance. It is organized into the six major program areas discussed below and is funded at about $60 million per year (FY96). The NRC research funding has been sharply declining in recent years. Activities that stimulate collaborative international research, cooperation with DOE and industry, and support the university nuclear engineering departments are being encouraged.

Reactor Aging Program

The goal of the reactor aging program is to provide data and analysis tools necessary to identify (anticipate), quantify (inspect, validate), manage, and regulate the effects of aging in NPPs for the current license periods and license renewal. The subjects of interest include reactor pressure vessel (RPV) embrittlement and thermal annealing; fracture analysis methods; environmentally assisted cracking of safety-critical systems and components; nondestructive evaluation techniques; steam generator tube and electric cable degradation; and inspection, surveillance, testing, and maintenance technologies for various mechanical components. Current and near-term deliverables include data to validate the RPV annealing rule and regulatory guide, a revised PTS regulatory guide, implementation of improved fracture mechanics methods into the ASME Code, validated models for steam generator tube severe accident analysis, revised guidelines and supporting data for electric cable qualification, and revised criteria for evaluating licensee in-service testing (IST) programs for pumps and valves.

Reactor Structural Performance Program

The goals of the Reactor Structural Performance Program are to (a) provide information needed to develop regulatory acceptance criteria for judging NPP site suitability; (b) assess and validate analytical methods for structural performance; and (c) determine the adequacy of margins of existing facilities. This program addresses the seismological, geological, and geotechnical factors associated with plant siting. Subjects of interest include inspection of aged/degraded NPP structures and components; assessment of the design and operational capacities of NPP structures, systems, and components; earth sciences investigations; and siting and structural aspects of non-reactor facilities such as gaseous diffusion plants and independent fuel storage facilities. Current and near-term deliverables include a trial implementation of the NRC, DOE, and EPRI guidance on conducting probabilistic seismic analyses; revised Regulatory Guides 1.60, 1.61, and 1.92; seismic data from large-scale main steam and feedwater piping systems; data from large-scale concrete containment pressure tests; an assessment of the effects of grease leakage from prestressing tendons on concrete containment strength; and data from seismic proving tests of concrete containments.

Probabilistic Risk Assessment Program

The goals of the Probabilistic Risk Assessment (PRA) Program are to (a) support risk-informed regulation by developing guidance and methods for PRA and (b) develop insights on the application of PRA through reviews of the IPEs and IPEEEs. The current and near-term products include Regulatory Guides in the area of overall PRA, inservice inspection (ISI), IST, quality assurance (QA), and Plant Technical Specifications. Other products include PRA methods for human reliability analysis, organizational performance evaluations, fire risk, plant aging, digital I&C, and consequence uncertainty. In addition to these R&D activities, this program also performs IPE and IPEEE reviews and issues appropriate regulatory documentation and insight reports.

Thermal Hydraulics Program

The goals of the Thermal Hydraulics Program are to (a) develop and maintain thermal-hydraulics experimental capabilities and analytical tools for the independent assessment of NRC licensee submittals and (b) analyze and evaluate NPP operating events and safety issues to assure an appropriate basis for regulation. Subjects of interest include plant transient analysis, plant transient code improvements, thermal hydraulic testing, fuel behavior, and reactor physics analysis. Current and near-term deliverables include correction of currently identified deficiencies in the existing thermal-hydraulics codes, completion of the AP600 related experiments, and completion of the FRAPCON and FRAP-T6 codes with high-burnup-fuel properties. Longer-term deliverables include a new state-of-the-art thermal-hydraulics code to replace the existing thermal-hydraulics codes, data to support the future code, and high-burnup-fuel cladding ballooning and quench data from simulated loss-of-coolant accident (LOCA) tests.

Control, Instrumentation, and Human Factors Program

The goals of this program are to (a) develop a credible basis of understanding of the performance characteristics of digital I&C systems, including software reliability and man-machine interface issues, and (b) develop methods for assessing human and organizational performance for use in regulatory applications. Subjects of interest include hybrid control rooms, root cause investigations, human performance evaluations, environmental qualification of digital I&C hardware, programming languages and CASE tools, adequacy of industry standards, guidelines for evaluation of the human-system interface, and total system reliability and acceptability. Current and near-term deliverables include development of a technical basis (reports) for hybrid and advanced control rooms and for staffing levels at operating plants, a revised Regulatory Guide 1.8, a new Regulatory Guide 1.1.64 (time response criteria for safety-related operator actions), a complete revision to the HPIP, a new Regulatory Guide on EMI/RFI, and data on the effects of smoke on digital I&C equipment.

Severe Accidents Program

The goals of the Severe Accidents Program are to (a) develop and maintain tools for analysis of severe accidents and (b) expand the experimental base (through international collaboration) to understand and quantify severe accident phenomena. The technical issues of concern include fuel-coolant interactions, hydrogen combustion, lower head integrity, debris coolability, and radioactive source terms. The work includes the further development of various severe accident computer models. Current and near-term deliverables include completion of (a) the fuel-coolant interaction experiments designed to evaluate the chemical augmentation of the energetics, (b) the high-temperature hydrogen combustion experiments, (c) the RASPLAV program, (d) the in-vessel cooling experiments, and (e) the lower head failure experiments. Other near-term deliverables include updated releases of the MELCOR, SCDAP, and CONTAIN codes; complete peer reviews of the VICTORIA and the fuel-coolant interaction codes; and analyses in support of the AP600 review.

3.2 Office for Analysis and Evaluation of Operational Data

The Office for Analysis and Evaluation of Operational Data provides the NRC with independent analysis of operational data and serves as the focal point for the assessment of operational experience through the review, analysis, and evaluation of the safety performance of both reactor and nuclear material facilities. The office collects, analyzes, and disseminates operational data; assesses trends in performance; evaluates operating experience to provide insights into, and to improve the understanding of, the risk-significance of events; conducts reliability studies of risk-important systems; analyzes human performance in operating events; and produces periodic Performance Indicator, Abnormal Occurrence, and Accident Sequence Precursor Reports. The office is also responsible for the NRC's Diagnostic Evaluation Program, Technical Training, and Incident Investigation and Response Programs. The Office spent about $13 million for contractor support in FY96, of which, about half went for R&D-related activities to support its mission. Examples of these R&D activities are listed below.

- Development of enhanced algorithms that utilize increased types of operational data (e.g., allegation data, regulatory fines, O&M costs, etc.) to predict poor or declining performance of operating commercial NPPs. This will primarily be used to support the semiannual review of the commercial NPP performance by the NRC senior managers.
- Development of risk-based performance indicators for the commercial power plants. This process has been underway for a long time, and the Office of Analysis and Evaluation of Operational Data (AEOD) has planned on incorporating the results of several operating event analysis programs into the development of the risk-based performance indicators.

3.3 Office of Nuclear Material Safety and Safeguards

The Office of Nuclear Material Safety and Safeguards develops and implements NRC policies for non-reactor nuclear and radioactive material activities such as uranium recovery activities; fuel fabrication and fuel development; medical, industrial, academic, and commercial uses of radioactive isotopes; safeguards activities; transportation of nuclear materials; away-from-reactor spent fuel storage; low-level and high-level radioactive waste disposal; and nuclear facility decommissioning. The Office of Nuclear Material Safety and Safeguards sponsors some R&D in support of their mission.

4.0 INDUSTRY SPONSORED R&D

4.1 Babcock & Wilcox Owner's Group

4.2 Boiling Water Reactor Owner's Group

4.3 Westinghouse Owner's Group

The Westinghouse Owners Group (WOG) historically has conducted R&D programs on a very limited basis, relying on other industry organizations to provide the needed R&D effort, most notably the EPRI. However, the WOG does conduct some programs to address issues that other industry organizations are unable to address when the need is identified to support the continued safe operation of its members plants, or when the benefit of such an effort could provide a significant O&M cost savings to the membership. The WOG has conducted or is conducting programs, some in conjunction with other organizations, which address material aging issues and O&M cost-saving items.

For material aging issues, the programs are:

(1) Reactor Vessel Closure Head Penetration Alloy 600 Program: Determine the effect of penetration microstructure and material type on PWSCC susceptibility, and assess the mitigative techniques for PWSCC initiation and growth rates. Program deliverables will include a methodology for the members to assess their unit(s) susceptibility, inspection guidelines, repair techniques, and possible mitigative options.

(2) Reactor Vessel Internals Bolting Program: Develop and qualify a new material for reactor vessel internals bolting that will extend the life of this component. Program deliverables will include an assessment of the current bolting material, testing of bolts removed from service, operational safety assessment, and tooling requirements for bolt inspection and replacement.

(3) Charging Pump Shaft Failure Program: Identify and demonstrate a new replacement pump shaft material for achieving improvement in service life for this component. Program deliverable will be a report on the various materials tested.

(4) Reactor Vessel Annealing Program: Verify that the reactor vessel and appurtenances' dimensional stability is maintained during and after an in-situ annealing process, which included heating curves, homogeneity of temperatures, temperature gradients, temperatures experienced by primary concrete structure, and validation of computation models for these parameters. Program deliverables will be the reports documenting the tests performed, pre-test predictions and post-test results, validation of the computation model, and procedures developed and used for the annealing demonstration.

(5) Reactor Vessel Fracture Toughness Testing Program: Determine applicability and demonstrate the new transition region fracture toughness techniques and work with the industry to have these techniques incorporated into the ASME codes. Program deliverable consist of technical reports detailing the results of the testing performed to support the development of the appropriate ASME code cases.

(6) Guide Tube Support Pin Replacement Material Program: Develop and qualify a new pin material and design that will alleviate SCC concerns and significantly extend the operational life of these components. Program deliverable will be reports on the design of a new guide tube support pin and qualification of the new material.

For O&M cost-saving items, the programs are:

(1) Application Specific Integrated Circuit (ASIC) Replacement Cards Development program: Develop a new I&C process protection system hardware platform that offers the advantages of state-of-the-art digital technology in a software-less form. The new hardware platform will be an ASIC mounted on new printed circuit boards designed to interface directly with the existing analog system hardware. Effort includes design, qualification, and licensing of the ASIC-based replacement boards for use in NPPs. Program deliverable will be the reports with the manufacturing design information, documentation of the qualification process, and licensing information.

(2) GOTHIC Shutdown Assessment Model program: Develop models for the Westinghouse 2, 3, and 4 loop plants using the GOTHIC computer code for use in assessing the plant conditions during shutdown operations that would provide plant capabilities and responses to both operational cases and postulated accident cases. Program deliverable will be the generic 2, 3, and 4 loop model shutdown codes.

(3) Reactor Coolant Chemistry Initiatives: Based on current plant operations and chemistry data, assess and determine the optimum chemistry management that will lead to reduced shutdown radiation fields,

optimize practices in regard to production and release of fission products to improve outage schedules, and assess chemistry management to minimize the production of corrosion products affecting fuel performance. Program deliverable will be a report that discuss the findings and recommendations for the control, production and transport of corrosion products, optimization of shutdown chemistry operations, and reduction in the rate of fuel clad crud deposition.

4.4 Fuel Vendor-sponsored Nuclear Energy R&D

Nuclear fuel vendors conduct R&D programs that are targeted at technology improvements to enhance market share. Currently U.S. fuel vendor R&D focuses on two areas: fuel reliability and fuel burnup extension. The two areas are closely related, because measures developed to extend the burnup capability must not impact reliability.

Although the overall fuel reliability has continued to improve over the past decade, three modes dominate the remaining failures: debris fretting, fretting from assembly hardware, and manufacturing defects. All of the vendors are addressing debris fretting through advanced filters incorporated into their assemblies. Westinghouse has developed and is supplying a debris filter bottom nozzle, a protective bottom grid, elongated bottom end plugs, and fuel rods coated with zirconia near the bottom to mitigate debris fretting. Framatome and Framatome Cogema Fuels have also developed an advanced anti-debris plate that includes electrochemically machined flow holes to achieve a lower overall pressure drop than current designs. GE has developed a debris filter lower tie plate and is assisting utilities with development of more effective foreign material exclusion programs. Siemens has developed the FUELGUARD lower tie plate, which utilize parallel curved blades to reduce debris fretting. ABB-CE has developed the GUARDIAN bottom grid for debris filtering. These companies continue to research additional modifications to further reduce the size of debris potentially entering the fuel assemblies.

The second type of failure is fretting from assembly hardware, usually grid spacers. Westinghouse has developed low-pressure drop grids and is investigating alternative placement of these grids to reduce flow-induced vibration. Siemens has developed new spacer and intermediate flow mixer designs that utilize a larger spring-to-rod contact area to reduce fretting. ABB-CE has developed an advanced grid that incorporates an “I” spring to increase the contact area and reduce fretting.

The final failure mode impacting reliability is undetected manufacturing defects. GE has implemented a laser welding procedure on all end caps to eliminate the potential for undetected, interconnected porosity in the Zircaloy bar stock. GE has also introduced a new upper end cap welding procedure that utilizes a single step rather than the girth weld / seal weld two-step procedure utilized previously. GE continues to develop “soft-handling” fabrication procedures to eliminate pellet chips and missing surface area. ABB-CE has adopted automated laser welding and 100% non-contact inspection of all grids to improve their performance. The other vendors continue to implement similar improvements.

The vendors are also investing substantial R&D budgets into burnup extension. Burnup is currently limited by fission gas release (and the associated fuel rod internal pressure and fuel swelling) and by cladding degradation. Fission gas release is being addressed through the incorporation of additives in the fuel matrix and through advanced fabrication processes that increase the average grain size of the fuel while maintaining an acceptable fuel creep rate to limit the potential for pellet clad interaction. Advanced fuel designs are also under development that provide additional room for rod axial growth during irradiation and provide additional plenum volume for additional fission gas release.

Cladding degradation is the subject of much of the current vendor-sponsored R&D. Westinghouse has developed ZIRLO, a proprietary zirconium-based alloy that contains niobium to minimize water-side corrosion. ABB-CE has developed OPTIN, a process-optimized low-tin Zircaloy-4, and is currently testing Anikuloy, an advanced zirconium-based alloy that includes niobium. GE is investigating process modifications to control the secondary phase particle sizes to optimize the cladding mechanical properties. Siemens is testing an advanced duplex liner cladding for BWRs that utilizes an iron-enhanced liner to reduce the severity of secondary hydriding of the zirconium liner following a primary cladding breach.